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# Experimental investigation of a downdraft biomass gasifier

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**Abstract**

An experimental investigation of a downdraft biomass gasifier is carried out using furniture wood and wood chips. The effect of equivalence ratio on the gas composition, calorific value and the gas production rate is presented. The calorific value of the producer gas increases with equivalence ratio initially, attains a peak and then decreases with the increase in equivalence ratio. The gas flow rate per unit weight of the fuel increases linearly with equivalence ratio. It is also observed that complete conversion of carbon to gaseous fuel has not taken place even for the optimum equivalence ratio. 

*Keywords:* Biomass; Gasification; Gasifier; Downdraft; Wood

## 1. Introduction

The utilisation of biomass is a very important source of energy in many parts of the world, especially for areas remote from supply of high-quality fossil fuels. Biomass energy conversion technologies especially pyrolysis and gasification have been substantially studied to promote renewable energy utilisation and solving partially the environmental issues. Various types of gasification systems have been developed and some of them are commercialised.

Narvaez et al. [1] have studied biomass gasification with air in a small pilot plant in a bubbling fluidised bed and the effect of several variables on the performance of the gasifier has been investigated. Brookes [2] discusses a gasifier for biomass waste and related volatile solids. Delgado et al. [3] discussed the upgrading (cleaning) of the raw hot gases from a bubbling fluidised bed biomass gasifier using cheap calcined minerals or rocks downstream from the gasifier. Goldman et al. [4] demonstrated the possibility of a two-phase counter-flow concept as a means of providing super adiabatic conditions, which are expected to enhance weak exothermic reactions and endothermic gasification reactions in the reforming zone. They have also developed a mathematical model based on a simplified case with a single source of reaction liberated energy to obtain temperature profiles in the gasification process. The United States Department of Energy has as a major goal in the development of cost-competitive technologies for the production of power from renewable biomass crops. Paisley and Anson [5] discussed the development and commercial demonstration of the Battelle high-through put gasification process power generating system. Hughes and Larson [6] used a modelling approach to simulate the effect of varying moisture content in the gasifier feed biomass. Jorapur and Rajvanshi [7] reported the commercial scale (300 kW) development of a gasification system using low-density biomass (sugar

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cane leaves and bagasse, bajra stalks, sweet sorghum stalks).

In the present paper, the results of the experimental investigation on a downdraft biomass gasifier are presented and discussed.

## 2. Experimental details

The experimental set-up consists of a blow-type downdraft gasifier with a cone structure, feeding system, start up system and an air supply system. Fig. 1 shows the main body made from a 600 mm diameter mild steel pipe with a total height of 2.5 m. The cone structure lined with refractory cement is 400 mm high, 600 mm diameter at the top and 200 mm diameter at the bottom. The cone is inclined at 60° to the horizontal to provide smooth gravitational movement of the wood to the combustion zone at the throat of the gasifier to facilitate the cracking of the tar. Feeding of biomass material or the solid fuel into the gasifier is carried out through the side door. The size of the biomass material used was equivalent to 50 mm cube. The air flow measured by a rotameter is supplied through a 40 mm diameter stainless-steel pipe with eight 10 mm diameter nozzles. The pipe is positioned along the longitudinal axis of the gasifier with nozzles positioned about 150 mm from the throat [8]. With this arrangement, air is gradually heated while flowing through the pipe before it exits to the combustion zone thereby assisting the combustion process.

Five-type K thermocouples are used to measure the temperature distribution inside the gasifier. The temperatures are measured at intervals of 30 s to record the thermochemical conversion phases: drying, pyrolysis, combustion and reduction. Another thermocouple measured the exit temperature of the producer gas. A typical temperature profile showing the various phases: drying, pyrolysis, combustion and reduction is shown in Fig. 2. The gas sampling train consists of a probe, condensation unit, PTFE filter, dryer, sampling bag and a suction peristaltic pump. Sampled gases are collected in 1 l non-permeable Teflon sampling bags and analysed using a TCD gas chromatograph to determine the gas composition and hence the calorific value.

It is important to highlight some of the experimental issues encountered during experimentation. The temperature in the combustion zone fluctuates

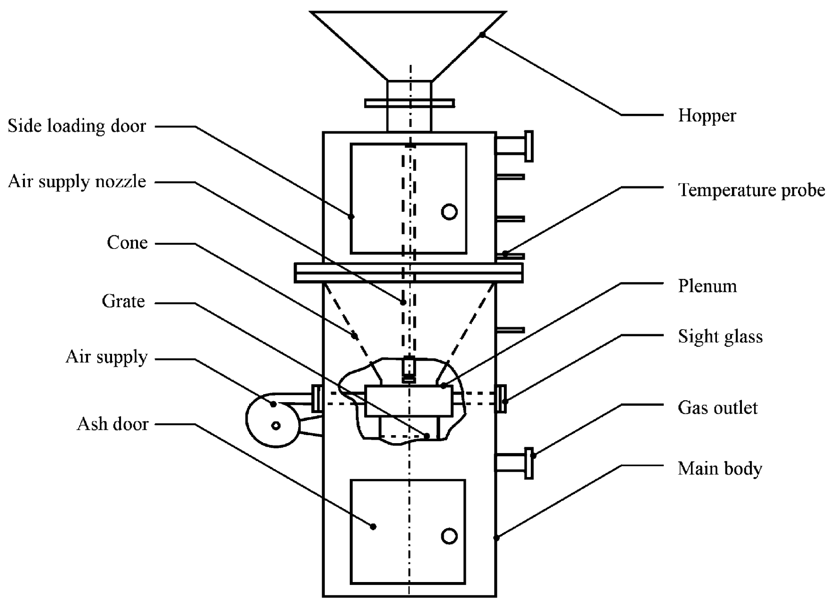


Fig. 1. Experimental set-up of the gasifier.

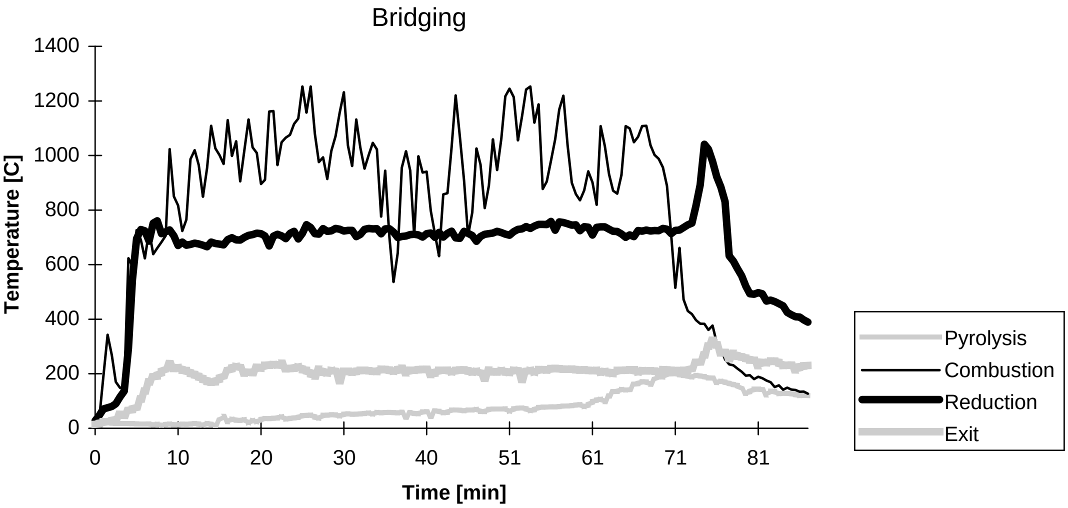


Fig. 2. Temperature profile showing the phenomena of bridging.

considerably because the temperature recorded by the thermocouple is not always that of the biomass material. When the glowing wood falls on the thermocouple, the temperature recorded is a high value whereas when the thermocouple is surrounded by the voids, it records a lower value.

Bridging is a normal occurrence in the gasifiers and its effect has been reduced by the use of a $60^\circ$ cone [9] that is higher than the angle of repose for wood chips ($45^\circ$) measured at ambient temperature. This phenomenon occurred while using furniture woods as well as the wood chips. Sometimes it occurred more than once during the operation of the gasifier. Further, bridging was observed when the inlet air flow is large and the temperature in the combustion zone is higher. This phenomenon of bridging can also be seen in Fig. 2.

In view of the high combustion zone temperature ($1000^\circ$C), the tar is cracked easily so that the biogas produced is having a very low content of tar.

## 3. Results and discussion

The performance of the biomass gasifier system is determined in terms of the cold gas and mass conversion efficiencies, the flow rate of the producer gas and the calorific value. The quality of the producer gas depends on various factors such as the moisture content of the feed, the air flow rate into the gasifier, the size of the wood, the position of the air inlet nozzle and the reduction zone volume. Gas analysis results are also presented to determine the development of the gas composition in the gasifier starting from cold. The gas analysis is used as a basis to determine the calorific value of the producer gas. A total number of 57 runs are conducted during the period of the study.

### 3.1. Equivalence ratio

In order to reduce the number of parameters on which the performance of the biomass gasifier depends, an equivalence ratio is defined to reflect the combined effect of airflow rate, rate of wood supply and duration of the run. The equivalence ratio for each run is calculated by

$$\text{Equivalence ratio } \phi = \frac{(\text{Flow rate of air supply}) \times (\text{Duration of the run})}{(\text{Mass input of wood}) \times (A/F \text{ for } \phi = 1)}.$$

$(A/F)$ for $\phi = 1$ is 5.22 $m^3$ of air/kg of wood.

The equivalence ratio for the gasifier is found to be in the range 0.268–0.43, which is within the range for ideal and theoretical gasification (0.19–0.43).

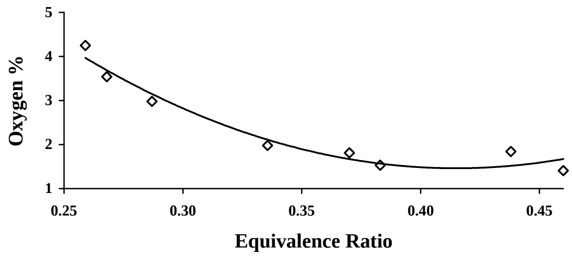


Fig. 3. Variation of percentage of oxygen with equivalence ratio.

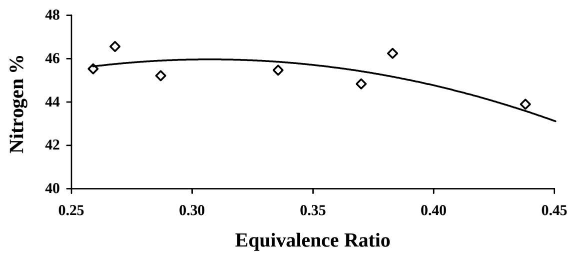


Fig. 4. Variation of percentage of nitrogen with equivalence ratio.

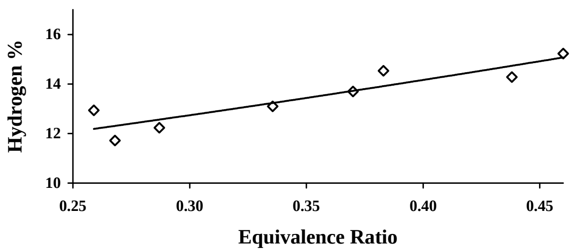


Fig. 5. Variation of percentage of hydrogen with equivalence ratio.

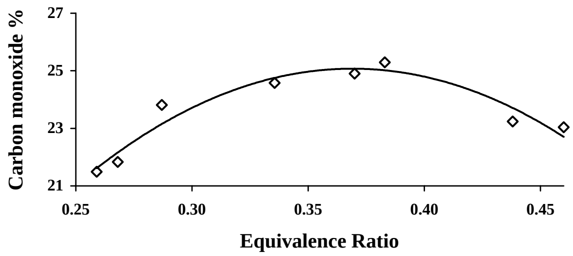


Fig. 6. Variation of percentage of carbon monoxide with equivalence ratio.

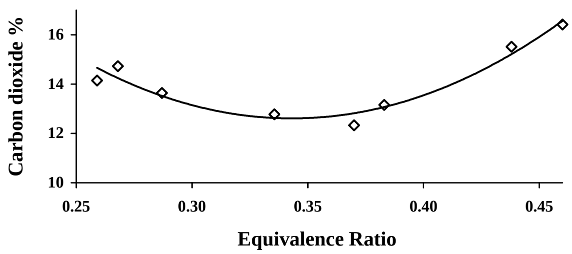


Fig. 7. Variation of percentage of carbon dioxide with equivalence ratio.

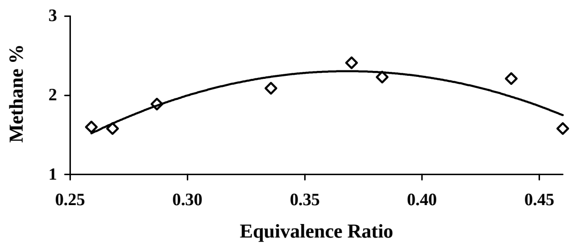


Fig. 8. Variation of percentage of methane with equivalence ratio.

### *3.2. Gas composition*

The gas composition and the calorific value of the wood gas are found to be similar to those reported by other researchers [8,10,11]. The average gas composition is: 1.69% $O_2$, 43.62% $N_2$, 14.05% $H_2$, 24.04% CO, 14.66% $CO_2$, 2.02% $CH_4$ and $C_2H_6$ detected as traces in most of the runs with a concentration of 0.01%. The formation of $CH_4$ is unstable as it dissociates into CO and $H_2$ in the reduction zone.

Figs. 3–8 show the percentage of the components of the producer gas against the equivalence ratio. The percentage of $O_2$ decreases with the increase in equivalence ratio up to about 0.43 and then increases. The percentage of $N_2$ decreases with the increase in equivalence ratio. The percentage of $H_2$ increases linearly with the equivalence ratio. CO concentration is the most significant contribution to the calorific value of the producer gas. The percentage of CO increases with the equivalence ratio up to some peak value and then starts decreasing. The variation for $CO_2$ is a decreasing and increasing trend just opposite to that of CO. The decrease in the percentage of $CO_2$ shows better conversion into CO in the reduction zone.

Table 1
Average performance for selected runs

| Run | Density ($kg/m^3$) | Calorific value ($MJ/m^3$) | Power output from the gasifier (kW) | Cold gas efficiency (%) | Mass conversion efficiency (%) | Equivalence ratio | Remark |
|---|---|---|---|---|---|---|---|
| 12 | 1.11 | 4.65 | 49.81 | 67.65 | 98.83 | 0.268 | Wood chips |
| 15 | 1.10 | 4.77 | 65.04 | 68.37 | 98.39 | 0.259 | Wood chips |
| 16 | 1.13 | 5.19 | 44.93 | 76.68 | 90.12 | 0.287 | Wood chips |
| 40 | 1.08 | 5.31 | 55.68 | 73.46 | 82.09 | 0.356 | Furniture wood +charcoal |
| 41 | 1.05 | 5.62 | 57.81 | 80.92 | 75.87 | 0.383 | Furniture wood+ charcoal |
| 45 | 1.10 | 5.24 | 42.47 | 86.80 | 86.14 | 0.438 | Furniture wood + charcoal; reloading |
| 46 | 1.09 | 5.56 | 48.29 | 82.49 | 86.74 | 0.37 | Furniture wood + charcoal; reloading |
| 54 | 1.08 | 5.20 | 44.45 | 81.77 | 90.37 | 0.46 | Furniture wood + charcoal larger reduction zone size |

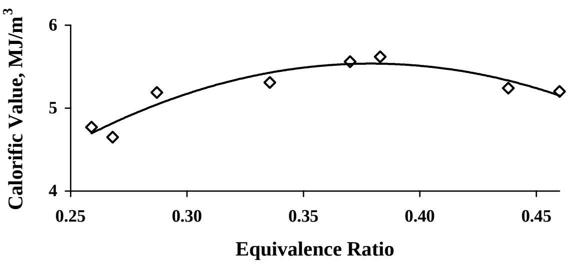


Fig. 9. Variation of calorific value with equivalence ratio.

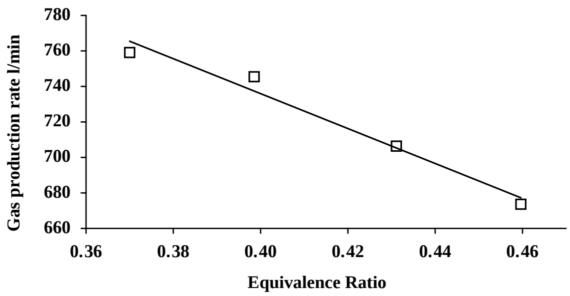


Fig. 10. Variation of gas production rate with equivalence ratio.

### 3.3. Calorific value of the gas

Table 1 shows the calorific value, the cold gas and the mass conversion efficiencies for varying equivalence ratio and wood consumption rate. It was found that more steady and consistent calorific values are obtained towards the end of each run and these are the values used in Table 1. Fig. 9 shows the variation of calorific value against the equivalence ratio. The calorific value increases with the increase in equivalence ratio up to a peak value at an equivalence ratio of 0.388 before it starts to decrease. The decrease in calorific value is due to the decrease in the percentage of CO. Other researchers have also observed a similar trend. The trend of the calorific value with equivalence ratio is in confirmation with Figs. 6 and 8 for CO and $CH_4$, respectively, which also peak around the same equivalence ratio. The higher heating value of the producer gas is calculated from the concentration of the combustible components and had an average value of 5.34 MJ $Nm^{-3}$.

### 3.4. Gas production

The producer gas flow is measured at regular intervals of 15 min and integrated over the period of wood consumption. The average flow rate of the producer gas leaving the gasifier was found to be 744.23 l/min for an air supply flow rate of about 400 l/min. The pressure generated in the gasifier is 5.01 kPa. Fig. 10 shows that the gas production rate decreases with the increase in equivalence ratio. For a given air supply and duration of the run, equivalence ratio increases with the decrease in the mass of the fuel and consequently the combustible material also reduces. This explains the reason for decreasing trend of gas production with the increase in equivalence ratio for a batch-type gasifier. However, the gas production rate per unit weight of fuel increases linearly with the equivalence ratio as shown in Fig. 11. Similar trend has been obtained by Ergudenler et al. [12].

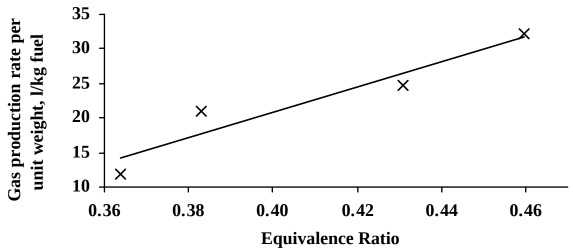


Fig. 11. Variation of gas production rate per unit weight of the fuel with equivalence ratio.

### 3.5. Performance of the biomass gasifier system

Table 2 shows the performance of the biomass gasifier system. The energy input and output for the gasifier, cold gas efficiency of the gasifier, power output from the generator coupled to an I.C. Engine run on biogas produced in the biomass gasifier, overall efficiency and the specific consumption of the biomass fuel are presented in this table. The producer gas is fed into a generator set and the power consumed in the electrical load is used to calculate the overall efficiency of the biomass gasifier system. The overall efficiency is found to be an average of 11.15% with a maximum of 15.46%. Hoi [8] obtained an overall efficiency of about 17.8%, whilst Hollingdale [10] obtained 21.2%.

The specific consumption of the biomass material is found to be an average of about 1.98 kg/kW h with a minimum value of about 1.49 kg/kW h obtained for run 44.

### 3.6. Uncertainty analysis

An experimental investigation is not complete without estimation of the uncertainties associated with the measured quantities and the final calculated values. The technique used to calculate the uncertainty values follows that of Kline and McClintock [13]. The accuracies of the rotameter, gas chromatograph and feed weighing machine are 10 l/min, 0.01% and 0.2 kg, respectively. Based on these, the uncertainty associated in the calculation of the calorific value is 6.3%.

### 3.7. Mass closure

The ultimate analysis of the biomass material used is 47.3% C, 5.8% H, 45% O, 0.8% N and 1.1% ash. Mass closure for C, H and O is obtained by calculating and comparing the C, H and O content in the feed and air as well as in the output of the gasifier. The carbon content in the ash is found to be about 10% of the carbon content in the feed at the optimum equivalence ratio. However, this percentage increases to a maximum of 27% especially at equivalence ratios far from the optimum value. Thus, ash contains C in relatively large quantities when the biomass gasifier is not operating at the optimum conditions. As regards the hydrogen and oxygen mass closures are concerned, the differences between the input and output vary from 1% to 10%.

## 4. Conclusion

An experimental investigation of a downdraft biomass gasifier is carried out using furniture wood and wood chips under various operating conditions. An increasing and then decreasing trend with equivalence ratio, with a peak at about 0.38, is seen for

Table 2
Performance of the biomass gasifier system

| Run | Power input into the gasifier (kW) | Power output from the gasifier (kW) | Mass conversion efficiency (%) | Equivalence ratio | Efficiency of the gasifier (%) | Overall efficiency of the biomass gasifier system (%) | Specific consumption of wood (kg/kW h) |
|---|---|---|---|---|---|---|---|
| 40 | 75.79 | 55.68 | 82.09 | 0.356 | 73.47 | 10.63 | 2.00 |
| 41 | 71.44 | 57.81 | 75.87 | 0.383 | 80.92 | 8.13 | 2.58 |
| 42 | 57.35 | 38.83 | 71.50 | 0.3831 | 67.71 | 10.64 | 1.97 |
| 43 | 59.35 | 45.75 | 85.10 | 0.364 | 77.09 | 10.54 | 2.02 |
| 44 | 39.13 | 30.26 | 61.57 | 0.3831 | 77.33 | 15.46 | 1.49 |
| 45 | 48.93 | 42.47 | 86.14 | 0.438 | 86.80 | 12.34 | 1.74 |
| 46 | 58.53 | 48.29 | 82.49 | 0.37 | 82.50 | 10.28 | 2.06 |

the CO and $CH_4$. The variation of the calorific value with equivalence ratio shows a peak value indicating that there is an optimum equivalence ratio (0.38) for the best performance of the downdraft biomass gasifier. The gas production per unit weight of the fuel increases linearly with equivalence ratio.

The cold gas efficiency of the biomass gasifier is found to be of the order of about 80% whereas the overall efficiency of the biomass electrical power producing system is of the order of 10–11%. The specific consumption of the biomass material is found to be of the order of 2 kg/kW h.

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